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Models for comparing air-only and sea/air transportation of wartime deployment cargo

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THESIS

MODELS FOR COMPARING AIR-ONLY AND SEA/AIR TRANSPORTATION OF WARTIME DEPLOYMENT CARGO
by
Michael J. Theres
December 1998

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Second Reader:	David A. Schrady

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MODELS FOR COMPARING AIR-ONLY AND SEA/AIR TRANSPORTATION OF WARTIME DEPLOYMENT CARGO

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Submitted in partial fulfillment of the
requirements for the degree of

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ABSTRACT

When faced with an overseas contingency, efficiencies may be gained by using ships in conjunction with aircraft to transport military cargo from the Continental United States (CONUS) to an overseas Port of Debarkation (POD). This thesis evaluates a proposal to load air-transportable cargo aboard vessels at CONUS seaports and to ship that cargo to an appropriately located sea-air-interface (SAI) for further transport by air to the final POD. This bi-modal approach is profoundly different from the current uni-modal paradigm where cargo loaded on a given platform at the port of embarkation continues on the same platform to the POD. Two mixed-integer programming models compare the incumbent and candidate transportation paradigms. The models are formulated in the General Algebraic Modeling System (GAMS) and run on a desktop PC. Solutions for a typical set of overseas airlift-only cargo requirements are obtained in less than one minute for both the air-only and bi-modal models. This research concludes that the bi-modal paradigm is less efficient than the uni-modal paradigm with respect to lift asset utilization and timeliness of deliveries, but may have merit as supplemental transportation to alleviate the backlog of surge cargo in the early phase of a conflict. For instance, by pre-positioning cargo at the SAIs, we are able to reduce the aircraft inventory required to execute our Time-Phased Force and Deployment Database from 44 to 30.

THESIS DISCLAIMER

Specific computer code is not included in this thesis, although the programs developed in this research are available from the author or advisor. The reader is cautioned that these computer programs may not have been exercised for all cases of interest. While every effort has been made, within the time available, to ensure that the programs are free of computational and logic errors, they cannot be considered validated. Any application of these programs without additional verification is at the risk of the user.

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EXECUTIVE SUMMARY

The Department of Defense currently employs a uni-modal transportation paradigm to transport military deployment cargo to overseas Ports of Debarkation (PODs). This may not be the most efficient means of transporting cargo overseas. Currently, if cargo is loaded aboard a ship at the Point of Embarkation (POE), that cargo is transported to the POD on that ship. Likewise, if cargo is loaded aboard an aircraft, it is transported to the POD on that aircraft and does not change modes en route. A combination of sealift and airlift, linked at a Sea-Air-Interface (SAI), may prove to be more efficient, in terms of asset utilization and/or time, than a pure lift-asset strategy. This thesis develops two optimization models to represent the uni-modal and bi-modal approaches to cargo deployment. Through these models we explore the relative efficiencies of those competing approaches.

First, we develop an air-only model to represent the current uni-modal approach. In order to ensure the validity of our input database for both the uni-modal and bi-modal models, we limit our input data to a hypothetical Time-Phased Force and Deployment Database (known as a "TPFDD") that includes only *air-transportable* cargo representative of an air-only, overseas deployment. We thereby guarantee that the candidate cargo is air-transportable; this is a requirement for the use of the bi-modal concept.

Next, we develop a bi-modal, sea-then-air model which combines a POE-to-SAI sealift transit with an SAI-to-POD airlift. We implement the bi-modal model only after all cargo with latest delivery dates of approximately two weeks has been delivered by air.

We then assume that all cargo transported within the Continental United States travels by truck or railcar and that all subsequent aircraft missions originate at the SAI.

A comparison of the two models' solutions suggests that the bi-modal concept is less efficient than the current air-only approach with respect to lift asset utilization and timeliness of deliveries. Slower sealift transit times in conjunction with extremely large sealift cargo shipments result in sporadic arrivals of massive quantities of cargo on "short-fused" schedules. This requires a large SAI aircraft inventory to affect any semblance of timely delivery to the APOD. In fact, the bi-modal model requires more aircraft to achieve results inferior to the air-only model.

Although our research in this thesis does not support the bi-modal concept as a replacement for the air-only, uni-modal concept, we believe that the bi-modal approach deserves further consideration and possible application in a less pure form. Three main avenues for further research may be the investigation of (1) prepositioning non-perishable cargo at an appropriate SAI, (2) a phased hybrid approach where air-only is used exclusively for the first 30 days of deployment followed by a period of exclusive bi-modal transportation, and (3) a true hybrid approach where air-only, sea-only, and bi-modal transportation are used together. Preliminary computations for case (1) shows a reduction from 44 to 30 in the number of aircraft needed to execute the TPFDD if all cargo is prepositioned. This indicates that a modest reduction in aircraft might be achieved by prepositioning a large amount of cargo if this is realistic.

I.   INTRODUCTION

For large-scale deployments of military cargo from the Continental United States (CONUS) to overseas destinations, the Department of Defense (DoD) currently uses only a single mode of transportation between the port of embarkation (POE) and the port of debarkation (POD). This is called the "uni-modal transportation paradigm." If cargo departs a POE by air, it will arrive at its POD by air. Similarly, if it departs by sea, it will arrive by sea. This may not be the most efficient means of transporting cargo overseas, however. A combination of sealift and airlift, linked at a Sea-Air-Interface (SAI), may prove to be more efficient, in terms of asset utilization and/or time, than a pure lift asset strategy. This thesis compares the time-tested, universally accepted uni-modal transportation paradigm – this is the only transportation paradigm TRANSCOM now uses -- with a new "sea-then-air, bi-modal concept."

The bi-modal concept uses an SAI located somewhere between the POE and POD to transload cargo from sealift to airlift assets. Since sealift is used to transport cargo to the SAI, aircraft are only required to fly the remaining distance. An SAI located midway between the POE and POD could hypothetically decrease associated aircraft flight times by one half. With intuition as a guide, one may therefore believe that the bi-modal concept using an SAI might nearly double our airlift capacity. This thesis investigates the validity of this intuition and documents the relative transportation-asset and time efficiencies of the two alternative paradigms through the use of optimization modeling.

A. BACKGROUND

Historically, military cargo in support of overseas crisis operations has moved between a selection of CONUS POEs and Out of Continental United States (OCONUS) PODs without changing transportation modes. DoD's commitment to uni-modal cargo movement continues today. If cargo is loaded on a ship at a POE, it sails all the way to its POD. If cargo is loaded on an airplane at a POE, it flies all the way to its POD. In the terminology of DoD's Joint Operation Planning and Execution System (JOPES), the "Preferred Mode of Transport to the POD" is either sea or air and does not change en route. This current transportation philosophy, although universally accepted and implemented, does not consider possible efficiencies to be gained by shifting to a more flexible transportation paradigm that allows a change of modes between the POE and POD.

Because existing JOPES transportation modeling software, JFAST (Joint Flow and Analysis System for Transportation), is designed to support only the uni-modal transportation concept, it cannot be used to investigate any new, bi-modal approach. In the absence of such software, we have been tasked with conducting a comprehensive, analytical study to investigate the possible efficiencies to be gained through the implementation of the bi-modal concept.

B. SCOPE, LIMITATIONS AND GENERAL ASSUMPTIONS

In order to effectively model, analyze, and compare the incumbent and proposed transportation concepts, we must consider mathematical networks that represent the time-phased nature of military force deployments. One network will represent the incumbent

paradigm by utilizing only air assets to transport military requirements from the air POE (APOE) to the air POD (APOD). The other will represent the bi-modal concept by transporting cargo by sea to an SAI and onto the APOD by air. A premise of this thesis is the existence of a suitable SAI. Thoughtful examination produces a set of characteristics, which an SAI must possess in order to make the bi-modal approach a viable option. These include:

- The sea leg between the POE and SAI is straightforward. If no significant land avoidance is required, the ship may follow great circle routes, the shortest possible distance between two points on the globe. This should reduce ship transit times and allow an increase in sealift "voyages."

- The distance between the SAI seaport and airport is minimal. If the seaport and airport are more or less co-located (hours by rail or truck, rather than days), the transition from sea to air mode should not add a consequential delay to the arrival of cargo at the final POD.

- The second leg of transport, the air leg, is less than 3500 nautical miles (n.m.), the maximum load/maximum non-stop distance for Air Mobility Command (AMC) aircraft. This would allow the forward deployment of airlift assets at the SAI and would ensure direct, non-stop legs from SAI to final APOD without the need for aerial refueling.

We will consider two hypothetical SAIs that possess these requisite characteristics. These SAIs, could represent any number of real seaport/airport combinations anywhere in the world. We will assume that SAI-I is a combination of seaport and airport located

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within two miles of one another. We will further assume SAI-II is some airfield within one day's rail or truck transit time of SAI-I so that cargo sealifted to the SAI-I seaport can be ground-transported to SAI-II for airlift to the APOD. We have chosen to model SAI-II as air-only to represent an extension of SAI-I's airlift capacity. Since, compared to airlift, sealift accommodates unusually large shipments, a single ship may deliver cargo in excess of a single airfield's capacity thereby necessitating some form of reserve capacity. SAI-II provides this capacity.

Given SAI-I and SAI-II as candidates, the initial focus of this thesis is to develop two optimization models, one that accurately reflects the current uni-modal approach and a second that includes the proposed SAIs in a bi-modal representation of the same transportation requirement. Once completed, these models become the foundation of a comparative analysis that evaluates the relative efficiencies of the two approaches with respect to lift-asset allocation and cargo-delivery tardiness. (We ignore the increase in misdirected or damaged cargo caused by transloading; it will be seen that this omission does not change the results of this thesis.) Subsequent sensitivity analyses of specific parameters will probe the bounds of the solutions and further explore specific concerns, such as:

- How many C-17 cargo aircraft are utilized under the bi-modal concept to yield results comparable to the uni-modal concept? This will give us an idea of how many C-17s, if any, can be employed in support of some other mission resulting from efficiencies gained by employing the bi-modal approach.

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- Using the current C-17 fleet size, how much can we improve delivery times, if at all, by using the bi-modal concept? Initial bi-modal test runs will be made without regard to APOD MOG (maximum aircraft on the ground) capacity constraints. This will reflect the maximum, intrinsic lift-asset capacity and will represent an upper bound on achievable lift-asset and cargo-delivery volume. If, in fact, the bi-modal concept shows an improvement in delivery times, similar model runs considering MOG will demonstrate the impact of the APOD MOG constraints on the delivery schedule.

- In the bi-modal analysis, what would be the effect of expanding and contracting each of the SAI's capacity on lift-asset allocation and the delivery schedule?

For simplicity, the following assumptions and respective justifications limit the scope of the research in this thesis:

- Only one type of sealift platform, the Cape J Class Container Ship (CJ) (Toppan [1998]) and one type of airlift platform, the C-17, will be considered in the analysis. The CJ reflects a generic container ship to which DoD would have access in the event that the bi-modal paradigm is adopted. The C-17 is DoD's newest, most versatile airlift asset and is likely to be the future choice for DoD airlift. Since we are testing the relative capabilities of two different transportation *concepts* and *not the capabilities of the specific platforms* used to execute the concept, using the same lift platforms with the same capabilities in both models should allow a valid comparison. If, as a result of this thesis,

the bi-modal concept proves to be more asset- or time-efficient, a more refined fleet representation could be the topic of follow-on research.

- A single-war scenario will be considered with no other Major Theaters of War (MTWs) active. This assumption allows the use of the full complement of lift assets to test the two transportation paradigms. If the new paradigm uses fewer assets to execute the same mission, the remaining assets would be available for assignment to other missions.

- Candidate cargo will be only that cargo with APOD latest arrival dates (LADs) between 17 and 90 days after the day deployment operations commence (C-day). Cargo with LADs of less than 17 days will certainly be transported by uni-modal air and will not be considered here. Day 90 is an arbitrary cut-off date for the end of the surge phase in an MTW and was suggested for use by the research sponsor.

- Only cargo planned to be transported by air under the current plan will be considered as candidate cargo for the new model. Although this assumption limits us to a small subset of required cargo, it assures that all cargo considered for bi-modal transportation is air-transportable, i.e., will fit on a C-17 for the SAI-to-APOD leg. This will allow us to draw conclusions about the proposed transportation concept itself. The determination of whether or not there exists sufficient candidate cargo to justify a paradigm shift is left as a topic for further research.

This thesis will present and discuss the two transportation concepts applied to a military transportation problem, that of a deployment from CONUS to some overseas location. We must limit our generalization to deployments that are characterized by the presence of appropriate SAIs as defined above. Time-Phased Force and Deployment Data (TPFDD) used as input to both the uni-modal and bi-modal models is our reasonable representation of a typical, air-only, CONUS-to-overseas deployment.

C. LITERATURE REVIEW

Dantzig and Fulkerson [1954] offer the first application of mathematical programming to time-dynamic military logistics optimization as well as time-dynamic network transportation problems.

Until recently, the computational demands of linear programming (LP) in modeling large-scale DoD force deployments allowed an insufficient level of detail for many analyses. Consequently, simulation was the method of choice for analyzing fleet mix and infrastructure requirements of such a deployment. Wing, *et al.* [1991] is the first example where optimization is successfully applied to such a problem and has since established the viability of optimization in this realm. Wing, *et al.* develop a time-dynamic LP as a response to the Mobility Requirements Study mandated by the National Defense Authorization Act of 1991. This model, called Mobility Optimization Model (MOM), is an example of a multi-commodity network flow problem similar to, but more general than, the topic of this thesis. It uses two interrelated networks, a network for cargo movement and a network for the flow of lift assets to carry that cargo. Additionally, it aggregates all "US bases into a single source node and all terminal

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destinations in the theater into a single sink." MOM also addresses the time-phased delivery of personnel and material and minimizes a function of cargo delivery tardiness. To some extent, each of these concepts is used as a basis for the modeling in this thesis.

Glaser [1991] develops an integer-programming model for scheduling the deployment of sea mines to different areas. Her model also uses two interrelated networks, a network for mine movement and a network for the flow of transportation assets to carry the mines. Constraints connecting the two networks ensure that mines do not move unless there are transportation assets to move them. Similar to MOM, Glaser uses two interrelated networks to model movements of material from supply points to demand points. Unlike MOM or this thesis, Glaser's model is only a single commodity network flow model. However, her model does allow transportation assets to return to supply points to transport additional material to meet demand. Treatment of lift-asset inventory is used and extended in both our uni-modal and bi-modal models.

Yost [1994] continues the integration of LP into the mobility-modeling arena with the development of THRUPUT, which offers a detailed routing structure, but is temporally static. Concurrent with Yost's work, the RAND Corporation developed CONOP [Killingsworth and Melody, 1994], which also focuses on airlift, but initially examined the efficacy of aerial refueling of airlifters in a contingency. Aviles [1995] incorporates most of the aforementioned modeling concepts in his master's thesis, entitled "Scheduling Army Deployments to Two Nearly Simultaneous Major Regional Conflicts." In his multi-commodity, time-phased, inter-linked transportation asset/commodity-movement network flow model, he not only minimizes a function of

delivery tardiness, but includes a factor that allows the manipulation of an incremental tardiness penalty. By incorporating this tardiness factor in our models, we can manipulate the cargo-shipment doctrine from preferring many shipments a little late to preferring few shipments very late. Yost's formulation contains further modeling considerations, such as maximum ship berthing availability, that we have included in our modeling effort as well.

Lim [1994], Morton, Rosenthal, and Lim [1995] and Rosenthal *et al.* [1996] extend THRUPUT with the development of THRUPUT II, which incorporates multiple time periods into Yost's work. Subsequently, RAND's CONOP model and THRUPUT II were merged into the Naval Postgraduate School/Rand Mobility Optimizer (NRMO) [Rosenthal *et al.*, 1997] which serves as an alternative and compliment to simulation for USAF strategic airlift analysis. NRMO is a very complex example of a multi-commodity, elastic demand model and would be too cumbersome to use in our "broad brush" uni-modal/bi-modal concept analysis. Current research [Damm, 1998] is incorporating sealift into the air-only NRMO model and may be helpful for follow-on research in the uni-modal/bi-modal comparison. NRMO is implemented in the General Algebraic Modeling System (GAMS)[Brooke, et al., 1996], and the code has been available to us. We have used NRMO extensively as a reference in the development of our own models, especially in the representation of time-phased cargo deliveries.

After an extensive review of work completed related to our analysis, we were unable to find any research that specifically targets our comparative analysis, although each separate work provides significant insight into some facet of our modeling task.

D. OUTLINE

The thesis is divided into five chapters with two appendices. The first chapter is the introduction and identifies the purpose and background of the thesis. The second chapter provides a general description of the uni-modal model, gives the mathematical formulation and then discusses the formulation in detail. The third chapter follows a similar progression for the bi-modal model. The fourth chapter discusses each model from a computer hardware and software perspective, continues with a sensitivity analysis of critical parameters, and concludes with a comparative analysis of the two transportation concepts. Chapter five first discusses the conclusions drawn from our analysis and points to possible areas for further research.

II.   AIR-ONLY MODEL FORMULATION

The analysis of this thesis requires us to realistically model both air-only and bi-modal transportation concepts. A comparison of the model efficiencies will allow us to determine if a change to the way DoD transports war materials is justified. The first step in the modeling effort is to mathematically represent DoD's current uni-modal transportation concept. We do this with our "air-only model" whose formulation is the subject of this chapter.

A. GENERAL DESCRIPTION

The United States Transportation Command (TRANSCOM) is one of nine Unified Military Commands within DoD and is responsible for coordination of all strategic transportation of military personnel and materials during peacetime and war. TRANSCOM has airlift assets stationed at APOEs throughout CONUS, standing ready to respond when called upon. Our model must represent these APOEs, their available aircraft inventories and their respective stockpiles of military cargo to be transported to the TPFDD-designated destination.

Depending on the requirements of the deployment, TRANSCOM will assign lift assets with required capabilities to the required APOEs (if not already assigned) to accomplish the mission(s) at hand. Assigned aircraft are loaded with the required cargo at their assigned APOE and flown to an APOD where the material is unloaded. At that time the aircraft is assigned to its next mission. Within the framework of assumptions that will be discussed later, our air-only model must reflect this concept.

Conceptually, the air-only model starts with a given level of aircraft inventory and assigns these aircraft to APOEs in the desired cargo-carrying configuration at the time required. This parallels TRANSCOM's initial airlift asset allocation discussed above. The transportation schedule is driven by the Commander in Chief (CINC) of the region (hereafter called the "regional CINC") to which DoD is responding. The regional CINC has TPFDD data that contains all the information pertaining to lift requirements such as origins, POEs, PODs, destinations, amounts of cargo, and dates associated with each node.

The TPFDD is organized into rows called Unit Line Numbers (ULNs). Each ULN and its associated unit information, nodes, quantities, and dates is referred to as a "CINC's requirement" and reflects what planners feel is necessary to successfully execute a particular deployment plan.

Theoretically, TRANSCOM seeks to execute the military deployment as close to the TPFDD as possible. Aircraft are loaded and depart the APOE on or after the "available load date" (ALD; see Table 1 for a thorough presentation of JOPES terminology), but no later than necessary to arrive at the APOD before the LAD. The model is constructed to represent this. "Elasticity" is built into the model to reflect those instances when the schedule cannot be kept. For modeling purposes, we have also incorporated a parameter, called "*MAXLATE*," that represents a time after which the regional CINC considers the delivery useless. If demand cannot be met before LAD + *MAXLATE*, the demand goes unmet and a large penalty is assessed. Within the model's aircraft-movement network, an aircraft is assigned a mission with associated APOE,

configuration and departure time parameters according to TPFDD requirements. The

model removes the aircraft from inventory and returns it after a period of *RTTP* (plane

round trip time) which includes flight time to and from the APOD, APOD unload time,

and en route ground time for fuel and turn-around maintenance. Within the model's

cargo-movement network, the model ensures the TPFDD-required cargo is transported to

the destination or is represented as unmet demand. Since only one APOD exists in this

particular analysis, we have chosen not to explicitly model this APOD in the aircraft-

Origin (ORIG)	Port of Embarkation (POE)	Port of Debarkation (POD)		Destination (DEST)	
Ready to Load Date (RLD)	Available to Load Date (ALD)	Earliest Arrival Date (EAD)	Latest Arrival Date (LAD)	Required Delivery Date (RDD)	CINC's Required Delivery Date (CRD)

Table 1. Illustrates JOPES terminology for the collection of transportation nodes associated with the transportation of military cargo. Unique names for dates associated with cargo movements at each node facilitate in scheduling time-phased shipments of military cargo.

movement network and, instead, view it only from the perspective of the APOE. (Note:

The APOD remains vital to the cargo-movement network.) For modeling purposes, we

maintain a generic "model inventory" for those aircraft not currently executing a mission;

in reality these aircraft are physically anywhere between the APOD and the next APOE

to require airlift assignment. Given that the model assigns an aircraft from inventory to

carry cargo from a CONUS APOE to an assigned APOD, the aircraft will execute the

mission and return to inventory after an *RTTP*. The model inventory accounts only for

number of aircraft regardless of APOE and cargo configuration. Once an aircraft is assigned to a mission, cargo configuration and APOE are assigned and maintained through completion of that mission. Once the assigned mission is complete, the model is free to assign that aircraft to another mission with a different APOE and cargo configuration.

B. AIR-ONLY MODEL ASSUMPTIONS

The air-only model consists of two interrelated network models, a cargo-movement model, and an aircraft-movement model. The cargo-movement network represents the flow of various types of cargo from designated CONUS APOEs to the in-theater APOD. The aircraft-movement network represents the flow of aircraft from CONUS APOEs, to the APOD, and back again. Constraints link the two networks to ensure that cargo does not travel from one point to another without an available lift asset.

In order to simplify the transportation network, CONUS APOEs are aggregated into six regional APOEs and the various APODs are aggregated into one APOD. These six "regional" or aggregated APOEs (henceforth simply referred to as "APOEs") and a single aggregated APOD (henceforth "APOD") are represented as nodes in the network. These are expanded by time and cargo type. The arcs of the model represent the possible movements of cargo between these APOEs and the APOD during possible and allowable movement times as required by the CINC's TPFDD.

Conceptually, the aircraft-movement network comprises seven nodes, one inventory node and six APOE nodes, each expanded by time. Aircraft-movement arcs represent the possible movement of aircraft, in time and space, so that aircraft are

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assigned to APOEs based on the quantity and type of cargo to be shipped. Aircraft outbound from an APOE ultimately return to inventory after a given *RTTP* and await further assignment. The actual mathematical model, however, is simplified so as to consist purely of inventory nodes expanded by time and connected by arcs that represent potential aircraft round trips. Additional parameters, such as APOE and cargo configuration assignments are carried on the arcs as well. Constraints link the cargo and aircraft-movement networks to ensure that cargo only travels from one port to another when aircraft with sufficient and appropriate capacities are available to carry that cargo between the designated ports at the same designated times.

The air-only model calculates its aircraft asset requirement by minimizing the sum of:

1) penalties for cargo delay at APOD,

2) penalties for unmet demand, and

3) a small artificial cost to deter unnecessary aircraft missions.

C. THE CARGO-MOVEMENT NETWORK

The cargo-movement network represents possible movements of required cargo from different APOEs to the final APOD. The nodes of the network, consisting of six APOE nodes equally spaced throughout CONUS, and one APOD node centered in the destination region, are expanded by time, which is given in units of days. The arcs of the network correspond to cargo movements between ports and the times at which these movements occur.

See Figure 1 for a conceptual presentation of the network nodes and the flow of cargo.
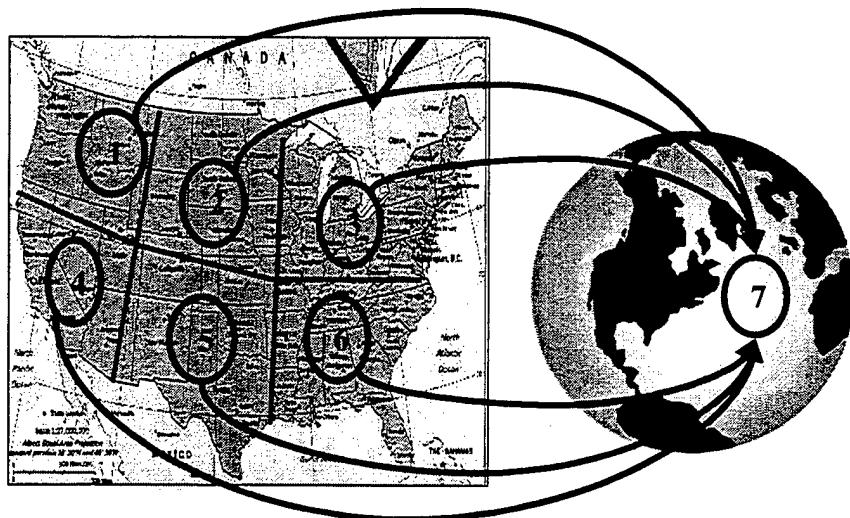
Figure 1. Conceptual Air-Only Network. This figure shows six CONUS APOEs (nodes 1 – 6) and the APOD demand point (node 7) located at some hypothetical overseas location (probably not in the middle of the Atlantic Ocean). This figure is a conceptual view only and is not intended to represent exact geographic divisions nor a complete mathematical network.

Nodes one through six are the APOE supply nodes of the network and represent an aggregation of transportation requirements by CONUS region. Node seven represents the cargo-movement network's demand point at the APOD. The seven nodes are:

    1 = Northwest CONUS

    2 = North-central CONUS

    3 = Northeast CONUS

4 = Southwest CONUS

5 = South-central CONUS

6 = Southeast CONUS

7 = APOD demand point located at some overseas location.

The cargo requirements, identified by APOE and cargo type, start at their respective APOE node at the earliest ALD for that cargo type and APOE combination. The TPFDD specifies three different cargo types [Secretary of the Air Force, 1997]:

bb = breakbulk (can be lifted on any aircraft),

ovr = oversized (can be lifted on C-5, C-17, C-141, C-130 aircraft), and

out = outsized (due to size, requires the use of a C-5 or C-17 aircraft).

The amount of supply at each APOE is, again, driven by the CINC's TPFDD and is equal to the in-theater demand for the ULN(s) associated with the respective APOE. At some allowable time t, i.e., t in the range [ALD, LAD – one-way travel time + MAXLATE], designated cargo is loaded aboard assigned aircraft. The variable x_{it} represents the number of short tons (stons) shipped at time t in support of the CINC's requirement i. Since standard TPFDD delivery data has a time resolution in days, we have maintained our model resolution in days as well. To this end, we have incorporated our model's two to four hours of aircraft loading and unloading time into the one-way travel time (*TTP*) and *RTTP* parameters. The loading capacity per aircraft is assumed to be 45 stons of any "pure" cargo load (i.e., each aircraft is loaded with only one type of cargo). This assumption has been generally accepted in previous military transportation

modeling [Killingsworth and Melody, 1994] and gives an accurate reflection of aircraft loading doctrine.

Cargo is moved between APOEs and the APOD on appropriately configured aircraft and within the maximum aircraft cargo capacity. With the model's time resolution in days, the difference in travel times from the various APOEs to the APOD is insignificant and allows us to assume constant *TTP* and *RTTP* regardless of the APOE. Despite this assumption, however, we deliberately maintain the distinction between APOEs in both the aircraft-movement and cargo-movement networks to preserve the identity of regional cargo and lift-asset requirements. This assumption allows the model to remain consistent with the TPFDD's time resolution of days and is also consistent across both models in the comparison.

Since cargo cannot move without aircraft, the model requires that we interlink the cargo network with the aircraft-movement network. The aircraft-movement network is the topic of the next section.

D. THE AIRCRAFT-MOVEMENT NETWORK

Conceptually, the aircraft-movement network first moves aircraft from an inventory node to the APOEs that require cargo movement. These aircraft then deliver cargo to an APOD and return to inventory awaiting further assignment. However, since there is only one in-theater APOD and the travel time to that APOD from any of the six APOEs is assumed identical, the aircraft-movement network can be simplified.

In the model, an aircraft will always return to inventory after completing an *RTTP*. This allows us to omit the time-expanded APOE and APOD nodes in the aircraft-

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movement network and allows us to move aircraft from inventory at time t and back to

inventory at time $t + RTTP$ without losing the desired network representation. Therefore,

the aircraft-movement network is mathematically modeled by one time-expanded

inventory node, inventory arcs between nodes in adjacent time periods and arcs that

represent APOE-APOD-APOE round-trips at particular times and in particular cargo

configurations (see Figure 2).
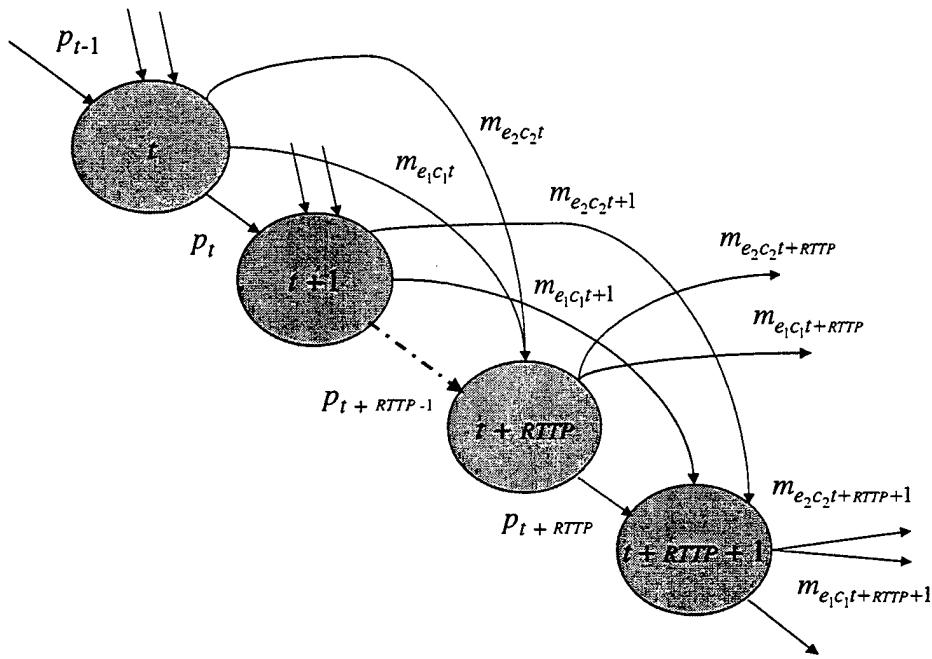
Figure 2. Mathematical Representation of Aircraft-Movement Network.
Aircraft are kept in inventory until they are required to carry a particular
cargo type, from a particular APOE, at a particular time t. The model then
assigns a mission in the proper configuration, and the aircraft departs the
inventory. The aircraft returns to inventory at $t + RTTP$ and awaits further
assignment with respect to APOE, configuration, and time. The variables p_t
and m_{ect} represent the plane inventory at time t and the assigned outbound
missions from APOE e, carrying cargo type c, at time t respectively. This
figure assumes only two cargo types, c_1 and c_2, are transportable from two
APOEs, e_1 and e_2, at times t and $t + 1$ respectively.

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Aircraft are kept in inventory until they are required to carry a particular cargo type, from a particular APOE, at a particular time. The model then assigns a mission in the proper configuration, and the aircraft departs from inventory. The aircraft returns to inventory at $t + RTTP$ and awaits further assignment with respect to APOE, configuration, and time. The variables p_t and m_{ect} represent the plane inventory at time t and the assigned outbound missions from APOE e, carrying cargo type c, at time t respectively.

E. AIR-ONLY FORMULATION

The following mathematical formulation represents the air uni-modal transportation paradigm currently in use by TRANSCOM subject to the discussed assumptions and simplifications.

1. Indices and Index Sets

$t \in T$ time in days, $T=\{1, 2, ..., 90\}$

$c \in C$ cargo type, $C=\{$breakbulk, oversized, outsized$\}$

$i \in I$ aggregated ULNs, $I=\{1,2, ..., \bar{I}\}$

$e \in E$ embarkation airports, $E=\{1,2,...,6\}$

2. Subsets

$T_i \subseteq T$ set of allowable shipping periods for aggregated ULN i

$T_{ce} \subseteq T$ set of allowable shipping periods for cargo type c at APOE e

$I_{ect} \subseteq I$ set of aggregated ULNs of cargo type c at APOE e at an allowable shipping period of $t + MAXLATE$ (*MAXLATE* defined below)

3. Data

$PCAP_c$ plane capacity (in stons) for cargo type c

REQ_i the amount of cargo in stons reflected in line item i of the CINC's TPFDD

LAD_i required delivery date for ULN i

TTP one way transit time from APOE to APOD

α exponent to influence tardiness penalties [Aviles, 1995]

$LATEPEN_{it}$ late delivery penalty defined as $\max\{0,(t + TTP - LAD_i)\}^{\alpha}$

$RTTP$ round-trip travel time

$UNMETPEN$ unmet demand penalty

$PINV$ initial inventory of planes

$MAXLATE$ shipment cannot be later than *MAXLATE* days

$MCOST$ artificial cost of an aircraft mission; deters unnecessary missions

4. Variables

p_t number of planes available for assignment at time t

m_{ect} number of aircraft missions assigned to carry cargo c from APOE e at time t

x_{it} cargo of ULN i shipped at time t (in stons)

u_i elastic variable representing unmet demand for ULN i (in stons)

5. Mathematical Formulation

$$\min_{x,u,m,p} \ \sum_i \sum_{t \in T_i} LATEPEN_{it} \ x_{it} +$$

$$\sum_i UNMETPEN \ u_i + \sum_e \sum_c \sum_{t \in T_{ce}} MCOST \ m_{ect} \qquad \text{(Obj 1)}$$

Subject to:

$$\sum_{t \in T_i} x_{it} + u_i = REQ_i \qquad \forall i \tag{1}$$

$$\sum_{i \in I_{ect}} x_{it} - PCAP_c m_{ect} \le 0 \qquad \forall e,c,t \in T_{ce} \tag{2}$$

$$-p_{t-1} - \sum_e \sum_c m_{ec,t-RTTP} + \sum_e \sum_c m_{ect} + p_t = 0 \quad \forall t \tag{3}$$

$$p_t, m_{ect}, x_{it}, \text{and } u_i \ge 0$$

$$p_t \text{ and } m_{ect} \text{ are integer}$$

where $m_{ect} \equiv 0$ if $t \notin T_{ce}$ and

$$p_0 \equiv PINV$$

F. DESCRIPTION OF THE FORMULATION

The primary objective of the air-only model is to meet demands for cargo of specified types, in theater, on given dates while minimizing a function of delay defined through $LATEPEN_{it}$. (Note: We could have chosen to minimize aircraft inventory so as to achieve no lateness. However, since we would like the uni-modal and bi-modal models to have a parallel structure and since preliminary research indicates that zero lateness may not be achievable in the bi-modal model, we choose to minimize lateness.) Here, $t + TTP$ is the departure date plus the travel time (the actual arrival time in theater),

and LAD_i is the latest arrival date for ULN i, so that the quantity $t + TTP - LAD_i$ represents the difference between actual and required arrival time at the APOD for requirement i. The max operator ensures that no penalty is assigned for early arrival. α is an exponent that influences the tardiness penalty and, for this thesis, is set to 1.5 because this author feels, in agreement with Aviles [1995], that it is somewhat better to have y tons of cargo one day late, than one ton of cargo y days late. We could include a similar, although probably smaller, penalty for early arrival at the APOD, but in view of this specific analysis, have not. Since one of our measures of transportation efficiency is how quickly each transportation model can deliver cargo to the APOD, penalizing for early delivery would interfere with this comparison.

The second term of the objective function accounts for the possibility of demand not being met at all:

$$\sum_i UNMETPEN \ u_i \ ,$$

where u_i is the demand for ULN i that was not met by day 90 or by $LAD_i + MAXLATE$, whichever is less.

The last term of the objective function deters unnecessary aircraft movement:

$$\sum_e \sum_c \sum_{t \in T_{ce}} MCOST \ m_{ect} \ ,$$

where m_{ect} represents the number of aircraft missions of type c, leaving APOE e at time t. $MCOST$ is a small penalty determined empirically.

The above objective is minimized subject to the following constraints that account for demand satisfaction, channel capacity for aircraft on given routes and a given time, and a balance of asset inventory.

Constraints (1) ensure that, within the TPFDD-permissible shipping times, in-theater requirements for ULN i are filled by appropriate cargo available at the APOEs or are absorbed by the variable u_i as unmet demand.

Constraints (2) link the cargo- and aircraft-movement networks. They ensure cargo moves between the APOEs and the APOD only when properly configured aircraft of sufficient and appropriate capacity are available at the APOE supplying the requirement.

Constraints (3) are the aircraft inventory-balance constraints. At every time period, they account for inventory carried over from the previous period, returning missions from previous taskings, new missions assigned to fly during that period, and aircraft remaining in inventory for assignment in the subsequent periods.

III. BI-MODAL MODEL FORMULATION

The second portion of our modeling effort culminates in a mathematical programming representation of the proposed sea-then-air, bi-modal transportation paradigm, whose output we will compare to the air-only benchmark. The bi-modal formulation is the subject of this chapter.

A. GENERAL DESCRIPTION

The primary client for this comparative study, the European Command (EUCOM), has provided us with a general bi-modal scheme from which to develop a model. The proposition is to load air-transportable cargo aboard vessels at CONUS seaports, to ship that cargo, via great circle routes, to an appropriately located SAI, and then to transload that cargo to aircraft for further transport to the final APOD. Within the framework of assumptions and simplifications discussed later in detail, our bi-modal model must reflect this concept.

The bi-modal model starts with a given level of ship and aircraft inventory. For modeling purposes, assets are maintained in this "model inventory" when not in use, but in reality could be physically located anywhere between the APOD and the next APOE having a lift requirement. The model assigns lift assets from the ship and aircraft inventories to SPOEs and SAIs, respectively, at TPFDD-required times. Ships are assumed to carry a mixture of cargo types and are loaded with cargo available at a particular SPOE at a particular loading time. On the other hand, as in the air-only model, aircraft in "pure" cargo configurations are assigned as required to execute the TPFDD.

This parallels the reality of initial "as-required" ship and aircraft allocation among seaports and airports during national crises.

We use the same TPFDD as in the air-only model; however, adjustments to the ALDs and LADs are required. Since our hypothetical TPFDD is specifically designed for air-transportable cargo, the differences between current ALDs and LADs do not allow sufficient transit time to make cargo shipments by sea feasible. In order to make a fair uni-modal/bi-modal comparison with like cargo tonnages, we adjust the ALDs to zero and shift all LADs to the threshold value at which the deployment can be completed without unmet demand. This is a reasonable adjustment since, in order to implement the bi-modal transportation paradigm, an actual TPFDD would require refinement to accommodate the slower transit times characteristic of a sealift and airlift composite.

Elastic, unmet demand constraints and the "*MAXLATE*" parameter are carried over from the air-only model unchanged, however.

One may believe that the proposed bi-modal concept could virtually double our airlift capacity by reducing original aircraft delivery distances by 50 percent. This initial intuition should be tempered by the consideration of a number of complicating factors, specifically in-CONUS transportation from the cargo origins to the SPOEs, the required transloadings at the SAI(s), the maximum SAI airport capacities (SAIMOG), and the SAI seaport berthing restrictions. We have incorporated model constructs to address these issues in the bi-modal model.

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B. BI-MODAL MODEL ASSUMPTIONS

The sea-then-air, bi-modal model consists of three interrelated networks, a cargo-movement network, an aircraft-movement network, and a ship-movement network. The cargo-movement network represents the flow of various types of cargo from designated CONUS origins to the destination APOD. The ship-movement network represents the flow of ships from CONUS embarkation points, the SPOEs, to the SAI seaport and back to CONUS. Similarly, the aircraft-movement network represents the flow of aircraft from the SAIs to the APOD and back to the SAIs. Constraints link the networks to ensure that cargo does not travel from one point to another without an available lift asset. In order to simplify the bi-modal transportation network, we have made the following aggregations:

1. CONUS origins have been aggregated into six regions (henceforth called the "origins"),

2. the CONUS SPOEs have been aggregated into two east coast hubs (henceforth called the "SPOEs"),

3. the in-theater destinations have been aggregated into one APOD, and

4. SAI-I has an airport co-located with its seaport. SAI-II has only an airport, but receives transloaded cargo from the SAI-I seaport.

These six origins, two SPOEs, two SAIs, and one APOD are represented as nodes in the conceptual, bi-modal transportation network (see Figure 3).

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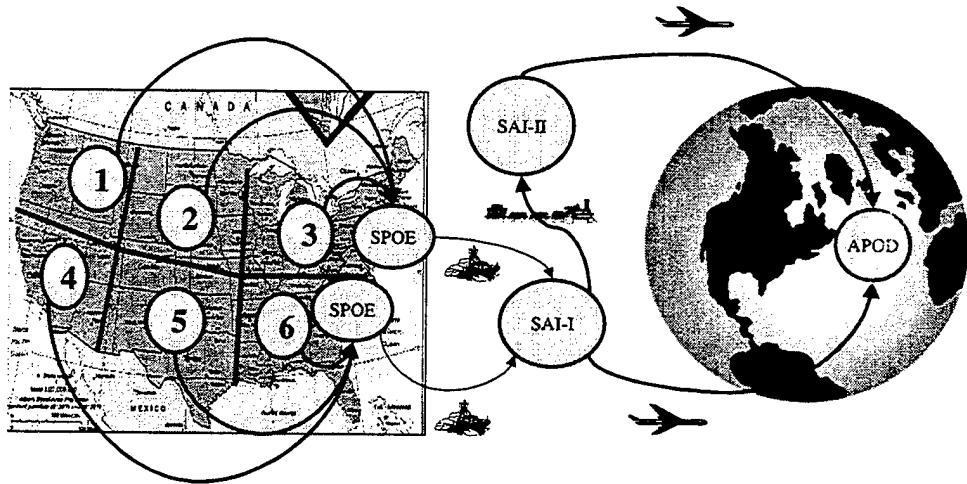
Figure 3. Conceptual Bi-modal Transportation Network. This figure shows six CONUS origins, the two SPOEs, the two SAIs and the APOD located at some hypothetical overseas location. This figure is a conceptual view only and is not intended to represent the mathematical networks models.

Subsets of these nodes are active in each of the inter-related networks and are expanded by cargo type, and/or time as appropriate. The arcs of the model represent the possible movements of cargo and lift assets between nodes in the network during TPFDD-permissible timeframes.

The conceptual cargo-movement network and the conceptual air-only network are pictorially the same (Figure 1 applies). Figure 1 shows the subset of Figure 3 that includes only those nodes active in the conceptual cargo-movement network. It

represents possible movements of required cargo from different CONUS origins to the APOD. The nodes of this network consist of six origin nodes equally spaced throughout CONUS and one APOD node centered in some hypothetical destination region. The arcs of the network correspond to cargo movements between CONUS origins and the APOD at TPFDD-permissible times.

In the mathematical version of the cargo-movement network model, the origins and APOD node are expanded by time (day). The arcs themselves correspond to the flow of cargo between the APOEs and the APOD at TPFDD-permissible timeframes. The time-delays on the arcs, however, represent a total en route time consisting of, not only transportation times, but also of SPOE load times, SAI pierside delay times, and SAI transload times.

Conceptually, the ship-movement network comprises three nodes, one inventory node and two SPOE nodes, each expanded by time. Ship-movement arcs represent the possible movement of ships, in time and space. Ships outbound from an assigned SPOE ultimately return to inventory after a given ship round-trip transit time (*RTTS*) and await further assignment. The mathematical model (Figure 4), however, has been simplified so as to consist purely of inventory nodes expanded by time and connected by arcs which represent round-trip ship voyages at particular times. Additionally, inventory arcs account for the number of ships from the previous period assignable in the current period and the number of ships from the current period available for assignment in the next. An additional parameter that designates the applicable SPOE is carried on the arcs as well. Constraints link the cargo and ship-movement networks to ensure that cargo only travels

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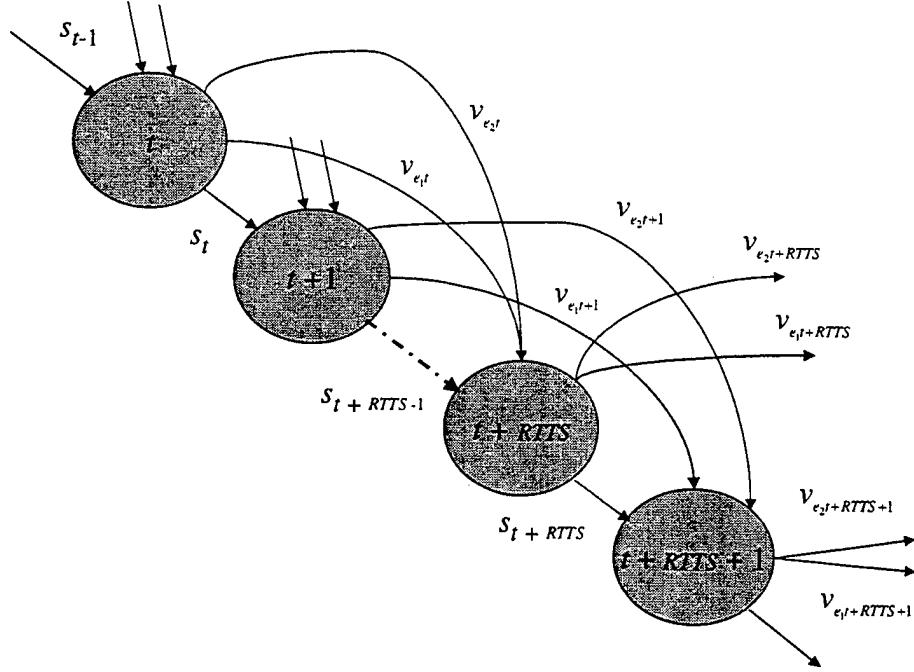
Figure 4. Mathematical Representation of Ship-Movement Network. Ships are kept in inventory until they are required to carry cargo from a particular APOE, at a particular time. At a particular time t, the model assigns a ship voyage that departs from inventory. The ship returns to inventory at $t + RTTS$ and awaits further assignment with respect to APOE and time. The variables s_t and v_{et} represent the ship inventory at time t and the assigned number of outbound voyages from APOE e at time t respectively. This figure assumes only two APOEs, e_1 and e_2, at times t and $t + 1$.

from one port to another when ships with sufficient capacities are available to carry that cargo between the designated ports at the same designated times.

The bi-modal aircraft-movement network is based on the air-only model's aircraft movement network (Figure 2). Once again, the aircraft-movement network is mathematically modeled by one time-expanded inventory node, inventory arcs between nodes in adjacent time periods and arcs that represent SAI-APOD-SAI round-trips at particular times. The only difference between the uni-modal and bi-modal aircraft-

movement networks lies in a change of the decision variable m's subscripts from ect to rct to reflect a departure point of SAI instead of APOE.

The bi-modal model calculates its sealift and airlift asset requirement by minimizing the sum of:

1) penalties for cargo delay at APOD,

2) penalties for unmet demand,

3) a small artificial cost to deter unnecessary aircraft missions, and

4) a small artificial cost to deter unnecessary ship voyages.

C. THE CARGO-MOVEMENT NETWORK

Much like the cargo-movement network in the uni-modal model, the bi-modal cargo network represents possible movements of required cargo from different origins to the APOD. The bi-modal model, however, forces cargo to travel to the APOD via an SPOE and a choice of two SAIs. In the cargo-movement network, this routing is not specifically modeled by additional nodes, but rather by varying transportation times depending on the route taken. Therefore, the cargo-movement network incorporates six origin nodes, equally spaced throughout CONUS, and an APOD node centered in the destination region. These nodes are expanded by time and cargo type. The arcs of the network correspond to TPFDD-permissible cargo movements between origins and APODs via a choice of SAI and SAI delay period.

The six origin nodes and one APOD node of the bi-modal cargo-movement network, identified by the numbers 1 through 7 in Figure 1, are defined as in the air-only

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cargo-movement network and represent an aggregation of transportation requirements by CONUS region.

As in the air-only model, cargo requirements are identified by ULN, origin, and cargo type. Additionally, in the bi-modal model, we have incorporated an SAI delay period which characterizes how long specific cargo is permitted to be held at the SAI before it is transloaded and delivered to its APOD. Furthermore, we have adjusted the ALDs and the LADs as discussed above. Cargo is available to leave the origin any time after the adjusted ALD and must leave no later than necessary to arrive at the APOD before the adjusted LAD plus *MAXLATE* factor. Finally, the cargo-movement network has associated side constraints that serve to:

1. Elastically meet all demand,

2. Enforce lift assets capacities, and

3. Ensure cargo does not move without an appropriately configured lift asset.

D. THE SHIP- MOVEMENT NETWORK

The ship-movement network is modeled after the aircraft-movement network of the air-only model. Conceptually, the ship-movement network moves ships from a model inventory node to the SPOE that requires cargo movement. These ships then deliver cargo to the SAI seaport and return to inventory awaiting further assignment. Since there is only one APOD and the travel time to that APOD from either SPOE is assumed identical, the ship-movement network can be simplified.

In the model, a ship leaving on a voyage at time t always returns to model inventory at time $t + RTTS$. This allows us to omit the time-expanded APOE and SAI

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seaport nodes in the ship-movement network. These round-trip ship-voyage arcs are replicated by SPOD. Therefore, the ship-movement network is mathematically modeled by one time-expanded inventory node, inventory arcs between nodes in adjacent time periods and arcs that represent SPOE-SAI-SPOE round-trips at particular times (see Figure 4).

The ship-movement network has associated side constraints that serve to:

1. Enforce ship capacities, and

2. Enforce daily SAI daily berthing restrictions.

E. THE AIRCRAFT-MOVEMENT NETWORK

The conceptual bi-modal aircraft-movement network is a direct replica of the air-only model's conceptual aircraft-movement network except that, instead of six APOEs, there are only two embarkation airports, namely, the SAIs. The single-destination simplification used in both the air-only aircraft-movement network and the ship-movement network holds for this network as well. Therefore, the mathematical bi-modal aircraft-movement network also comprises only one inventory node expanded by time and cargo type, inventory arcs between nodes in adjacent time periods and arcs that represent SAI-APOD-SAI round-trips at particular times. The model assigns aircraft from the model inventory in the required configuration at the required time to support the TPFDD. Aircraft return to inventory after a given *RTTP* awaiting further tasking. The aircraft-movement network has associated side constraints that serve to:

1. Enforce aircraft cargo capacities and

2. Enforce SAI daily MOG restrictions.

F. THE INTER-RELATIONSHIP OF THE CARGO-, SEA-, AND AIR-MOVEMENT NETWORKS

The cargo-, ship- and aircraft-movement networks are intricately related by time, cargo type, and points of origin, embarkation, and/or debarkation. The cargo-movement network spans the ship- and aircraft-movement networks and serves as the common thread linking the two. The cargo ALDs and LADs drive the time-phased relationship which determines allowable cargo departure and arrival times. The model assigns lift assets to support the requirements based on these departure and arrival times.

Cargo is available for loading onto vessels at the SPOE some time after the adjusted ALD plus a delay of $DELAY_{oe}$. $DELAY_{oe}$ reflects the delay between an origin and the applicable APOD and includes ground transportation time from the origin to the SPOE and ship loadout time. Similarly, cargo is available for loading onto aircraft at an SAI after a delay of $DELAY_{or\tau}$. $DELAY_{or\tau}$ is a parameter that reflects the sum of $DELAY_{oe}$, ship transit time, SAI cargo-transloading time, and SAI pierside-delay time. Lastly, the parameter $TT_{or\tau}$ represents the total travel time from a specified origin to the APOD via a given choice of SAI with an appropriate SAI delay.

Linking constraints ensure that cargo moves between embarkation and debarkation points only when an appropriate lift asset is available. Simultaneously, these constraints enforce lift-asset capacity limitations.

G. BI-MODAL FORMULATION

The following mathematical formulation represents the proposed bi-modal transportation paradigm subject to the discussed assumptions and simplifications.

1. Indices and Index Sets

$t \in T$ time in days, $T = \{1,2, \ldots, 90\}$

$\tau \in T'$ SAI delay period for cargo, $T' = \{1,2, \ldots, 8\}$

$c \in C$ cargo type, C={breakbulk, oversized, outsized}

$i \in I$ aggregated ULNs, $I = \{1,2, \ldots, \bar{I}\}$

$o \in O$ origin of cargo, $O = \{1,2, \ldots, 6\}$

$e \in E$ seaport of embarkation, $E = \{\text{North, South}\}$

$r \in R$ route cargo travels; via SAI r, $R = \{\text{I, II}\}$

2. Subsets

$T_i \subseteq T$ allowable shipping periods from origin o for ULN i

$T_{ir} \subseteq T$ allowable shipping periods for ULN i shipped from origin o to APOD via SAI r

$T_{cr} \subseteq T$ allowable shipping periods for cargo type c shipped from origin o to APOD via SAI r

$T_e \subseteq T$ allowable shipping periods for any cargo shipped from origin o to APOD via SPOE e

$I_c \subseteq I$ aggregate ULNs with cargo type c

$I_o \subseteq I$ aggregate ULNs having origin o

$I_{ot} \subseteq I$ aggregate ULNs at origin o at an allowable shipping period of $t +$ *MAXLATE* (*MAXLATE* defined below)

$O_e \subseteq O$ set of origins o being serviced by SPOE e

3. Data

REQ_i the amount of cargo (stons) reflected in ULN i of the CINC's TPFDD

$PCAP_c$ plane capacity (stons) for cargo type c

$SCAP$ ship capacity (stons) for total cargo

$SAIBERTH$ ship berth capacity (no. of ships) at SAIs' joint port

$SAIMOG_r$ max aircraft capacity at SAI r (no. of aircraft per day)

LAD_i required delivery date for ULN i

TTS one-way travel time (days) for ship between SPOE e and SAI

α exponent to influence tardiness penalties

$LATEPEN_{it}$ late delivery penalty defined as $\max\{0,(t + TTS - LAD_i)\}^{\alpha}$

$RTTS$ round trip travel time (days) for ships

$RTTP$ round trip travel time (days) for planes

$TT_{or\tau}$ one-way transit time (days) for cargo originating at o travelling to the APOD via SAI r with SAI delay τ

$DELAY_{oe}$ travel time (days) from origin o to SPOE e

$DELAY1_{or\tau}$ travel time (days) from origin o to SAI r plus SAI delay τ

$UNMETPEN$ unmet demand penalty

$PINV$ initial inventory of planes

$SINV$ initial inventory of ships

$MCOST$ artificial cost of an aircraft mission; deters unnecessary missions

$VCOST$ artificial cost of a voyage; deters unnecessary ship voyages

MAXLATE   shipment cannot be later than *MAXLATE* days

4.   Variables

p_t number of aircraft in inventory at the end of period t (available for assignment at time $t + 1$)

s_t number of ships in inventory at the end of period t (available for assignment at time $t + 1$

m_{rct} number of air missions to fly from SAI r at time t carrying cargo type c

v_{et} number of ship voyages assigned to carry cargo from SPOE e to the SAI at time t

$x_{irt\tau}$ cargo (stons) of ULN i shipped from origin via SAI r at time t with SAI delay of τ

u_i elastic variable representing unmet demand (stons) for ULN i

5.   Mathematical Formulation

$$\min_{p,m,s,v,x,u} \; \sum_{o} \sum_{i \in I_o} \sum_{r} \sum_{t \in T_i} \sum_{\tau} \mathit{LATEPEN}_{iort\tau} \; x_{irt\tau} +$$

$$\sum_i \mathit{UNMETPEN} \; u_i +$$ (Obj 2)

$$\sum_r \sum_c \sum_{t \in T_{cr}} \mathit{MCOST} \; m_{rct} + \sum_e \sum_{t \in T_e} \mathit{VCOST} \; v_{et}$$

Subject to:

$$\sum_r \sum_{t \in T_i} \sum_{\tau} x_{irt\tau} + u_i = \mathit{REQ}_i \qquad \forall \, i$$ (4)

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$$\sum_{o \in O_e} \sum_{i \in I_{o,t-delay_{o,e}}} \sum_r \sum_\tau x_{ir,t-delay_{oe},\tau} - VCAP \; v_{e,t} \leq 0 \qquad \forall\, e,t \qquad (5)$$

$$\sum_{i \in I_c} \sum_\tau \sum_{t-delay1_{or\tau} \in T_{ir}} x_{ir,t-delay1_{or\tau},\tau} - PCAP_c \; m_{rct} \leq 0 \qquad \forall\, c,r,t \qquad (6)$$

$$- s_{t-1} - \sum_e v_{e,t-RTTS} + \sum_e v_{et} + s_t = 0 \quad \forall\, t$$
$$\hspace{11cm} (7)$$

$$- p_{t-1} - \sum_r \sum_c m_{rc,t-RTTP} + \sum_r \sum_c m_{rct} + p_t = 0 \qquad \forall\, t$$
$$\hspace{11cm} (8)$$

$$\sum_e v_{e,t-TTS} + \sum_e v_{e,t+1-TTS} \leq SAIBERTH \qquad \forall\, t \qquad (9)$$

$$\sum_c m_{rct-TTP} \leq SAIMOG_r \qquad \forall\, r,t \qquad (10)$$

p_t, s_t, m_{rct}, v_{et}, $x_{irt\tau}$, $u_i \geq 0$, and
p_t, s_t, m_{rct}, and v_{et} are integer

where $\quad v_{et} \equiv 0$ if $t \notin T_e$,
$$s_0 \equiv SINV,$$
$$m_{rct} \equiv 0 \text{ if } t \notin T_{cr}, \text{ and}$$
$$p_0 \equiv PINV.$$

H. DESCRIPTION OF THE FORMULATION

The primary objective of the bi-modal model is to meet demands for cargo of specified types, in theater, on given dates, while minimizing a function of delay defined through $LATEPEN_{iortr}$. Here, $t + TT_{ort}$ is the sum of the actual departure date, the travel time from origin o to the APOD via SAI r, and the delay of τ days at the SAI awaiting further transportation. This sum corresponds to the actual arrival time of cargo at the APOD. LAD_i is the latest arrival date of ULN i so that the quantity $t + TT_{ort} - LAD_i$ corresponds to the difference between the actual and required arrival time for requirement i. The "max" operator ensures that no penalty is assigned for early arrival at the APOD. Once again, α is an exponent that influences the tardiness penalty and is set at 1.5, as in the air-only model.

The second term of the objective function accounts for the possibility of demand not being met at all:

$$\sum_i UNMETPEN\ u_i,$$

where u_i is the demand for ULN i that is not met by the end of the time horizon or the *MAXLATE* factor, whichever is less.

The last two terms of the objective function deter unnecessary aircraft or ship movement:

$$\sum_r \sum_c \sum_{t \in T_{cr}} MCOST\ m_{rct} + \sum_e \sum_{t \in T_e} VCOST\ v_{et}$$

where m_{rct} represents the number of aircraft missions carrying cargo type c departing SAI r at time t, and v_{et} represents the number of ship voyages departing SPOE e at time t.

MCOST and *VCOST* are small costs for aircraft missions and ship voyages, respectively, and are proportioned relative to the carrying capacities of aircraft versus ships.

The objective is minimized subject to constraints that account for demand satisfaction, channel capacities for both ships and aircraft on given routes, asset inventory balances, constraints that reflect SAI airport and seaport capacities, and finally non-negativity and integrality restrictions for the decision variables:

Constraints (4) ensure that within the TPFDD-permissible shipping times and subject to the ALD and LAD relaxations discussed above, requirements for ULN i are filled by appropriate cargo at the origins or are absorbed by the variable u_i as unmet demand.

Constraints (5) link the cargo- and ship-movement networks. They ensure cargo does not move unless a sealift asset is available at an appropriate SPOE with sufficient capacity.

Constraints (6) link the cargo- and aircraft-movement networks. They ensure cargo moves between the SAI(s) and the APOD only when properly configured aircraft of sufficient and appropriate capacity are available at the SAI supplying the requirement.

Constraints (7) and (8) are the ship and aircraft balance constraints, respectively. At every time period, they account for inventory carried over from the previous period, returning lift assets from previous taskings, newly assigned taskings that depart during that time period, and lift assets left in inventory for assignment in subsequent periods.

Constraints (9) are port capacity constraints for the SAI that limit the number of ships allowed pierside at the SAI on each day (to at most *SAIBERTH*).

Constraints (10) reflect the SAI airfield capacities ("MOG constraints").

IV.   COMPUTATIONAL RESULTS

In this section, we first discuss the data set used as a representative TPFDD for input to the air-only and bi-modal models. We then describe the resulting model sizes and the solution times. We perform a sensitivity analysis on each model to determine the effect of varying critical parameters. Finally, we present a comparative analysis of the relative efficiencies of the two competing transportation paradigms.

Both the air-only and bi-modal models are generated using the General Algebraic Modeling System (GAMS) [Brooke, et al., 1998]. A copy of the GAMS formulation can be obtained from the author or advisor. Both models are solved using the Optimization Subroutine Library (OSL) [IBM, 1991] on a desktop personal computer with a Pentium 166 megahertz processor. Graphics included in the appendices are generated through Microsoft's Excel 97 spreadsheet program including Visual Basic for Applications (VBA) [Microsoft, 1997].

A. THE HYPOTHETICAL DATA TEST SET

The hypothetical TPFDD used as input to our air-only and bi-modal transportation models is our best estimate of an actual overseas deployment in support of an MTW. The data set is very compact and represents an aggregation of similar cargo, shipped from geographically close regions, at like times to one consolidated destination. All cargo quantities are given in increments of 45 stons equivalent to a full C-17 load.

For the air-only model we have retained a realistic ALD/LAD spacing of k days. For the bi-modal model, however, in order to affect a feasible bi-modal delivery

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schedule, we are forced to amend the ALDs and LADs so as to achieve a minimum

spacing of at least $k + n$ days. Here k is the typical time difference (in days) between the

ALD and LAD and n is the minimum number of additional days required to admit a

feasible bi-modal model solution.

B. AIR-ONLY MODEL

We first run the air-only model several times with varying initial aircraft

inventories to establish a "zero-lateness threshold," i.e., the minimum inventory level that

allows TPFDD execution with no late cargo delivery. The air-only model comprises

2,187 variables, of which 353 are discrete, and 557 constraints. Generation and solution

times for each run are less than one second. Through these model runs we establish a

zero-lateness inventory threshold of 44 aircraft. The air-only model therefore

demonstrates that the current uni-modal, air-only transportation paradigm can execute our

TPFDD with 100 percent on-time delivery of all required cargo with a minimum of 44

aircraft. Of course, in reality, a few extra aircraft would be needed to deal with

unforeseen equipment failures and/or aircrew problems. However, these attrition factors

are assumed to be similar in both the uni-modal and bi-modal models and are therefore

disregarded.

Given a 100 percent, on-time delivery schedule, Figure 5 shows a daily mission

profile for an aircraft inventory at the threshold value of 44 aircraft.

C. BI-MODAL MODEL

We next run several permutations of the sea-then-air, bi-modal model in an attempt to achieve, as we have in the uni-modal model, a 100 percent, on-time delivery of all TPFDD cargo. Unfortunately, we are unable to effect a zero-lateness schedule with

44 Aircraft
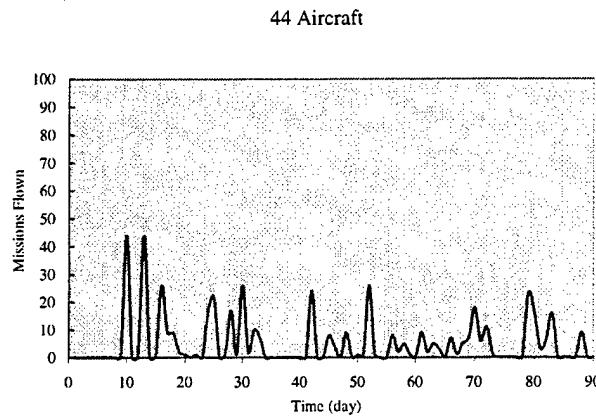
Figure 5. Uni-modal missions profile of number of misions flown per day.

any combination of air and sealift asset inventories. We can, however, ensure 100 percent delivery of cargo with some lateness (i.e., within our chosen *MAXLATE* factor of 3 days).

Due to long model computation times when using low initial ship and aircraft inventories, we choose to perform several runs limiting the total number of voyages to three ships. We arrive at three ships as an initial inventory solely on the basis of a known ship capacity and total TPFDD cargo to be moved. We first run the model to determine the actual voyage schedule, fix these voyages, and then explore the effects of varying aircraft inventory. This strategy serves to accelerate solution times drastically and still

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yields optimal solutions since the optimal restricted objective is the same as the unrestricted one.

Using the fixed-voyage model, we incrementally increase aircraft inventory from the established "uni-modal, zero-lateness threshold" of 44 aircraft to the minimum level at which u_i, the variable representing unmet demand, reaches zero. Through this procedure we establish the bi-modal minimum aircraft inventory at 70 aircraft. Although 70 aircraft employed bi-modally can satisfy 100 percent of demand, the required delivery schedule creates cargo lateness that cannot be eliminated regardless of aircraft inventory. Bi-modal, fixed-voyage generation and solution times for models with varying initial aircraft inventories are approximately 48 seconds. The bi-modal model consists of 84,012 variables, of which 560 are discrete, and 987 constraints. Figure 6 demonstrates the effect of varying aircraft inventory on delivery lateness and cargo "Not" delivered.

It appears that in order to achieve a reasonable number of on-time deliveries, even under our relaxed ALD/LAD bi-modal assumptions, the number of aircraft required to deliver cargo bi-modally exceeds the number required to execute the same TPFDD uni-modally. Reasons for this will be discussed in detail later, but, generally, the result can be attributed to slow ship transit times and the massive, discrete nature of the tonnages delivered.

D. COMPARATIVE ANALYSIS

This section addresses the direct implications of our uni-modal and bi-modal comparative model runs, we analyze the effect of expanding the SAI MOG, and we discuss the analyses we proposed in the introduction to this thesis.

**Voyages Constant at Three with Varying A/C Missions**
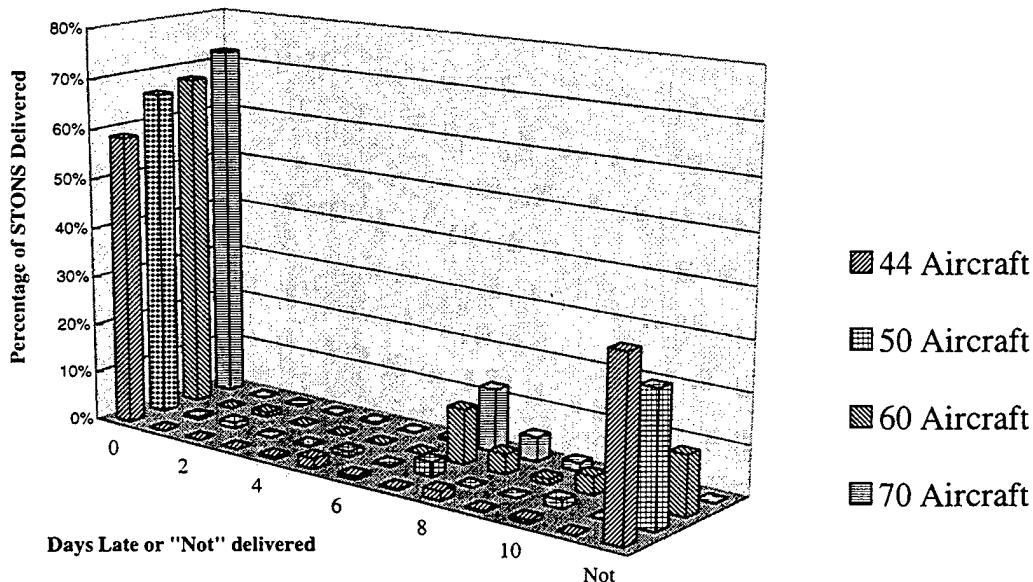
Figure 6. This figure demonstrates the effect of varying aircraft inventory on timely delivery of TPFDD cargo. Holding total ship voyages to exactly three, as aircraft inventory is increased from the uni-modal "zero-lateness threshold of 44 to 70 aircraft, cargo not delivered decreases to zero and on-time delivery increases from 59 to 72 percent.

A direct comparison of uni-modal to bi-modal transportation, given a TPFDD

designed specifically for execution by uni-modal air, may result in a failure to transport

even one ULN on time. The TPFDD must be modified to accommodate the sealift

portion by increasing the difference between the ALD and the LAD. Even with this

adjustment, however, we must consider the impact of relatively few, but very substantial,

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cargo deliveries to the SAI seaport. In order for the SAIs to better absorb these massive deliveries, we maintain an allowable SAI inventory delay of $\tau = 8$ days. In spite of these modifications, we must also maintain a minimum inventory of 70 aircraft to ensure delivery of 100 percent of required cargo while accepting some degree of lateness.

Figure 7 demonstrates the sporadic nature of flight operations required to support this bi-modal model. Notice that the large aircraft inventory is only required for 17 to 19 days with the given TPFDD. Although the required flight intensity is of short duration, such a large-scale diversion of lift assets is likely to adversely impact other worldwide mobility taskings.

**Missions Flown with an Initial Aircraft Inventory of 70 Aircraft (by SAI)**
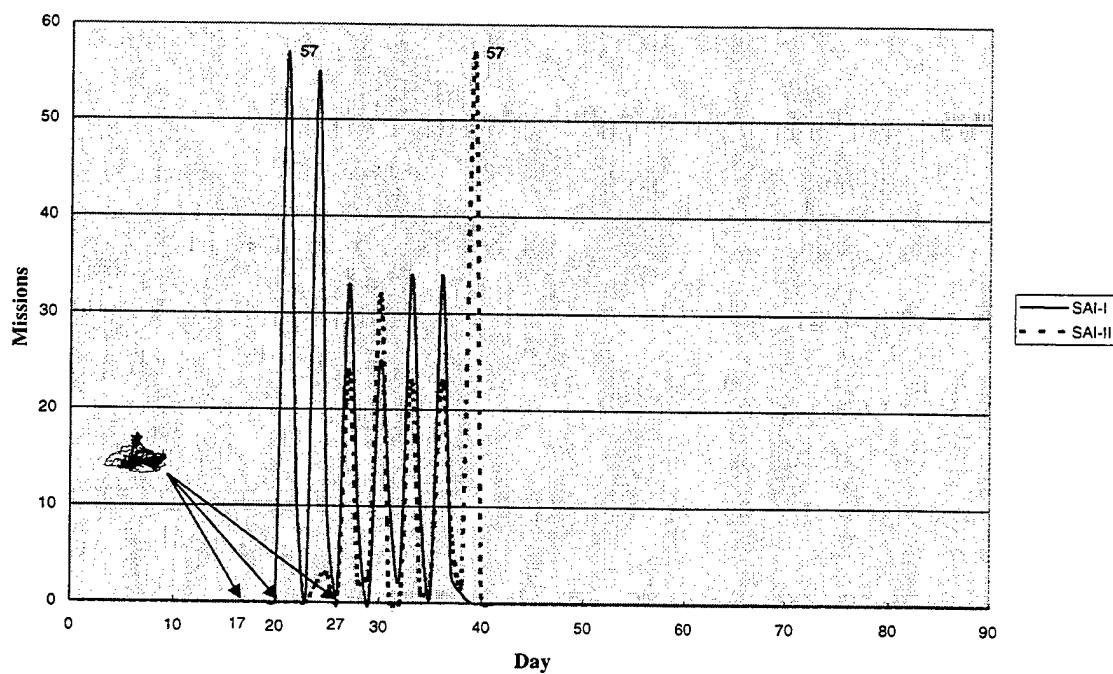
Figure 7. This figure reflects the required flight schedule by SAI to deliver 100 percent of TPFDD cargo to the APOD within a *MAXLATE* of three days with ship arrivals as indicated, on days 17, 20 and 27. This flight schedule also incorporates

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an allowable SAI delay period of $\tau = 8$ days. It is interesting to note that flight operations are limited to a duration of 17 to 19 days.

In the introduction to this thesis we raised the question, "How many C-17 cargo aircraft are utilized under the bi-modal concept to yield results comparable to the uni-modal concept?" We also asked a related question concerning possible benefits of employing the current level C-17 inventory bi-modally. In response to both of these questions, we must unequivocally state that: Even the projected FY07 C-17 maximum inventory of 83 aircraft employed in a bi-modal approach cannot achieve an on-time delivery schedule. Since the purpose of implementing a bi-modal transportation concept would be to improve over the current air-only approach, our research does not justify a change in transportation paradigm, but instead validates the uni-modal air approach.

Finally, we claim that expanding the SAI MOG limitations would have no effect on the delivery schedule. Since we fail to saturate either SAI (at a daily MOG of 64 aircraft when we employ the maximum FY07 C-17 inventory), increasing SAI MOG will not improve the delivery schedule (see Figure 8).

Although we set out to show that a bi-modal approach to the current uni-modal transportation paradigm would significantly enhance the timely delivery of deployment cargo to an overseas APOD while reducing the required number airlift assets, we seem to have shown just the opposite. Indeed, our research in this thesis does not support our initial intuition in the sense of a pure replacement for the air-only, uni-modal concept, but we believe the bi-modal approach deserves further consideration and possible application in a less pure form.

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MOG by SAI
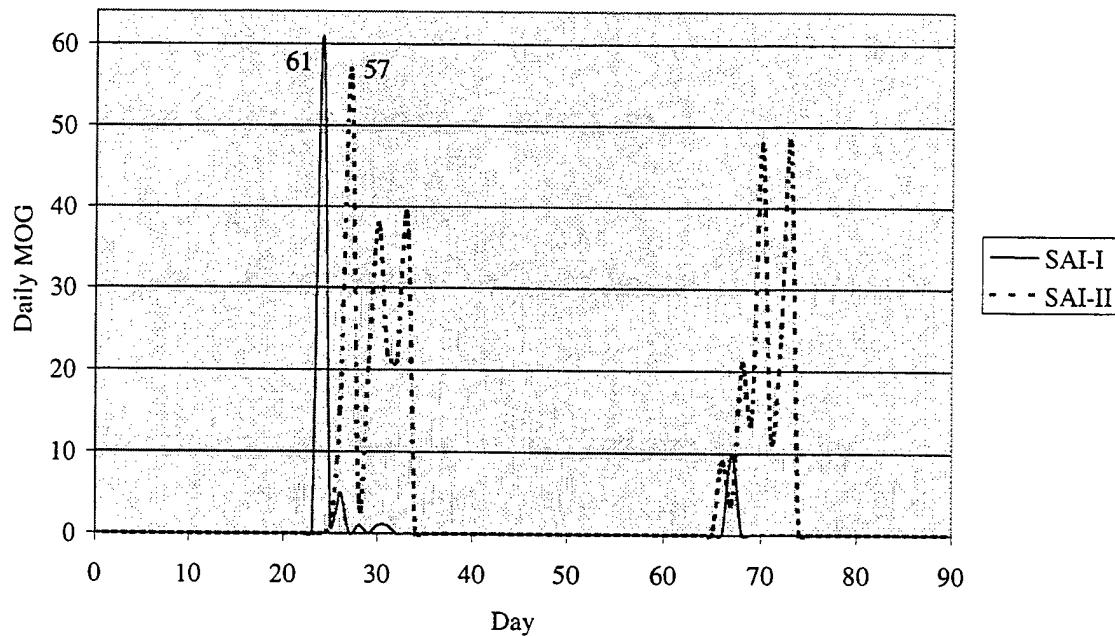
Figure 8. This figure shows the level of MOG utilized at the respective SAI over time with an initial inventory of 83 aircraft, the projected FY07 maximum C-17 inventory. Even at this level of inventory, the MOG constraint of 64 aircraft per day is not binding. Therefore, increasing the SAI MOG will not improve the delivery schedule.

V.   CONCLUSIONS

This chapter (1) summarizes problems with the sea-then-air, bi-modal concept as a replacement for uni-modal air, (2) discusses possible beneficial applications for the bi-modal concept, and (3) discusses possible areas for further research.

A. THE PROBLEM WITH SEA-THEN-AIR BI-MODAL

It seems clear from our analysis that, if we are looking for a direct substitution of one transportation paradigm for another, then the bi-modal approach shows little promise. The immediate result of this thesis is that to execute our modified air-only TPFDD using the bi-modal concept will require more lift assets and more time than we require to execute the unmodified TPFDD uni-modally.

We draw this conclusion because using a combination of sea and air assets, rather than strictly air, is unquestionably slower. The sea leg alone is many times longer than a the one-day air-only leg to virtually any global destination. The efficiencies we had hoped to gain through large-scale sea transport coupled with subsequent shortened airlift distances are more than offset by backlog inefficiencies generated at the SAIs due to relatively few, but very substantial sealift deliveries. (Recall that we ignored the impact of misdirected and/or damaged cargo caused by bi-modal transloading. Note that considering these factors would only exacerbate SAI inefficiencies and would reinforce our conclusions.)

A further complicating factor is the "tightness" of the air-only TPFDD ALD/LAD "window." Despite our modification that widens the window, cargo is already "running

late" by the time it arrives at the SAI seaport due to the relative slowness of sealift. This requires an excessive inventory of airlift standing ready at the SAIs in order to achieve any semblance of timely deliveries.

B. POTENTIAL APPLICATION OF BI-MODAL TRANSPORTATION

Although the sea-then-air, bi-modal concept cannot compete directly with air-only for the execution of an air-only TPFDD, it has potential application within a hybrid transportation scheme. The bi-modal concept could be applied in conjunction with uni-modal air and uni-modal sea. It could be utilized as a compromise form of transportation for cargo that does not truly merit air precedence, but goes by air just because sealift-only is too slow. On the other hand, there may be priority cargo that is sent via sea solely because airlift is saturated. Therefore, low priority airlift cargo and high priority sealift cargo would be candidates for bi-modal transportation within the hybrid transportation concept. Essentially, a hybrid transportation scheme would allow a new level of prioritization. It might also remedy an overdemand for uni-modal air in the surge phase of a conflict. During the Gulf War, the first few weeks generated such a backlog of air cargo that it eventually led to a complete logistics standstill.

> "With the lack of initial unit prioritization plus desired closure dates of 'now,' a cumulative movement requirement represented an airlift demand six to seven times normal capability." [USGPO, 1993]

The bi-modal concept, when used in conjunction with the current air-only paradigm, may help alleviate some of the backlog and contribute to the more timely delivery of surge phase, air-transportable cargo.

C. AREAS FOR FURTHER RESEARCH

In light of the error of our initial "intuition," and given the hybrid transportation scheme proposed in the previous section, we believe there are three main avenues for further research:

- Prepositioning: We could preposition a subset of non-perishable cargo at an appropriate SAI. This may truly double our airlift capacity by reducing the flight distances by 50 percent without introducing the complications caused by slow sealift transit times and cargo transloading.

- Phased hybrid: If we use air-only early in the conflict, say during the first 20 to 30 days, we could implement bi-modal transportation so as to time the arrival of ships at the SAIs to reduce the number of aircraft needed later in the conflict.

- True hybrid: We could use air-only, sea-then-air (bi-modal), and sea-only simultaneously.

The first area for further research, prepositioning, may allow us to realize our initial hope for doubling our airlift capacity. At the outset of this thesis research, we hypothesized that current airlift capacity could be virtually doubled through the shortening of airlift distances by 50 percent. But, we did not recognize the complications of receiving massive quantities of relatively "late" cargo at the SAIs, and thus cannot achieve the efficiencies we had hoped for using the bi-modal approach. We could eliminate these complications by prepositioning non-perishable, air-transportable cargo at the SAIs so that it is available for airlift on the first day of a military deployment. Since

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prepositioned cargo is within one day's travel time of the APOD and available for transport immediately, we could avoid the high aircraft inventories necessitated by the bi-modal approach's long sea-transit and transloading times. With only slight modifications to our air-only model, we are able to conservatively establish a zero-lateness threshold of only 30 aircraft in initial inventory for a "prepositioned model" versus 44 for our non-prepositioned air-only model. Additional research would be required to determine the feasibility of prepositioning cargo at the SAI. This prepositioning would have to be useful for many scenarios to be worthwhile and would have to be limited to non-perishable, low-maintenance items.

A phased approach combining air-only and bi-modal transportation should also be investigated. This approach would allow air-only for the first 20 to 30 days (instead of 16 in our current research) and would include air shipment of all surge-phase cargo; it is this cargo that accounts for the bulk of the lateness penalty when using relatively low initial aircraft inventories in our current research. Once the surge cargo is delivered, a shift to a purely bi-modal strategy would allow SAI arrivals to be scheduled to reduce the number of required aircraft.

We mention one final area for further research, namely, a truly hybrid transportation concept. This concept would include simultaneous use of all three transportation methods, specifically uni-modal air, uni-modal sea, and bi-modal (sea-then-air). Each of these concepts could be modeled and used simultaneously throughout the conflict as appropriate. If all three concepts are a part of the same optimization, the model could decide during which timeframes each concept should be used.

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